14.4 INVESTIGATION OF MESOSCALE PRESSURE AND TEMPERATURE TRANSIENTS ASSOCIATED WITH BOW ECHOES

Rebecca D. Adams* and Richard H. Johnson
Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado

1. INTRODUCTION

Bow echoes have been an established part of the literature since a 1978 technical report by Fujita– who not only coined the term, but also created a conceptual model showcasing the lifecycle of these systems. The bow echo's association with severe winds has also been both well-studied and well-documented, from Fujita's original work to the present. However, very little work has focused on surface features, such as pressure and temperature, associated with these storms. While the arrangement of these parameters as associated with squall lines has become highly recognizable (including the mesohigh, cold pool, and wake low; Johnson & Hamilton 1988, Loehrer & Johnson 1995), it is still uncertain how strictly these patterns can be applied to the smaller-sized members of the broad class of mesoscale convective systems (MCSs).

Utilizing the Oklahoma Mesonet, an observational network of detailed resolution in both time and space, a dataset of surface features associated with 42 different bow echoes in Oklahoma over four years was generated. These systems were examined to determine if there were any common patterns of behavior of the surface pressure and temperature fields associated with bow echoes, and to further determine if there are patterns that are unique to these phenomena. As will be seen, distinctive patterns of behavior were indeed observed, which presents possible opportunities for a more dynamical separation (other than an arbitrary size limit) of bow echoes from typically larger and more commonly occurring squall lines.

2. METHODOLOGY

2.1 *Dataset manipulation*

The Oklahoma Mesonet (described online at http://www.mesonet.ou.edu/public/) provides meteorological observations at five-minute intervals over the entire state, available over the past 13 years. For the purposes of this study, only the years 2002 through 2005 were examined, to correspond with available radar data. The diurnal cycle was then removed from the pressure observations; they were also corrected to a constant height (356.5 m, average height of all stations) using virtual temperature. In addition, a high-pass Lanczos filter (Duchon 1979) was run on the data to remove all the longer, synoptic timescales. Following the definition provided in the American Meteorological Society Glossary (2000), the upper (longer) end of the mesotimescale is the pendulum day, which for average Oklahoma latitude is 41.2 hours in length. Thus, the Lanczos filter was run to retain all features with a period shorter than this. After this procedure, a time-space transformation was also applied for each bow echo case, assuming 15-minute steady-state periods.

Subsequently, the data were objectively analyzed to a grid using multiquadric data analysis. During the years examined, 15-minute resolution composite NOWrad radar data were available from WSI (obtainable online through UCAR at http://locust.mmm.ucar.edu/WSI/). GEMPAK was utilized to contour the corrected, filtered, and gridded data, and overlay the resulting contours on the radar data.

2.2 *Bow Echo Definition*

The definition for a bow echo used in the study drew heavily on Klimowski et al (2000, hereafter K00). They utilized Fujita's original 1978 identification to require "a bow or crescent-shaped radar echo with a tight reflectivity gradient on the convex (leading) edge" which must be nontransient. However, Fujita's schematic also included an associated downburst, which can be difficult to identify solely by radar. Thus, K00 incorporated that the echo must appear to be "outflow dominated"; in other words the radius of the bow must get smaller with time. This decrease in radius is referred to as "active bowing" throughout the rest of this paper. Finally, the motion of the bow may not exactly correspond to the mean tropospheric steering flow. This defini-

**Corresponding author address:* Rebecca Adams, Department of Atmospheric Science, Colorado State University, Fort Collins, CO 80523-1371; adams@atmos.colostate.edu

tion was also utilized by Klimowski et al. (2004) in the creation of their classification system, which is closely related to the taxonomy used in this study.

The four years of radar data were examined, and all cases which fit the definition outlined above were set aside for examination. Further qualifications were required to account for the spatial organization of the Mesonet. In order to be able to see any associated surface features, the bow echo would need to be large enough to cover at least two Mesonet stations. The curved, bow shape must last at least one hour; active bowing must last longer than thirty minutes due to the temporal resolution of the radar dataset. Finally, the apex of the bow must be within Oklahoma during those time constraints (excluding the panhandle, due to its low density of observation stations).

2.3 *Bow Echo Classification*

As previously stated, the basic structure of Klimowski et al. (2004, hereafter K04) was reused for the classification procedure in this study. This procedure was chosen by the authors for both its simplicity as well as its easy application to radar data. Echoes were examined by their type of initiation as well as their structure when mature. K04's convective initiation types included the merger of weakly organized cells (termed "merger" in this paper), bowing of a squall line ("linear"), or bowing of a supercell. The third category was simplified for this study to bowing of an isolated single cell ("isolated"), as often not enough information was available to determine whether the cell was officially supercellular. Occasionally the bow echo would form outside the state of Oklahoma where the process of initiation remained undetected; in those cases the bow was classified by mature structure only. Mature structure designations were also adopted from K04: the classic bow echo (CBE; not contained within a larger mesoscale complex or near other convection, but larger than a single thunderstorm), the bow echo complex (BEC; a bow echo containing other types of convection), and a squall line bow echo (SLBE; a bowing segment contained within a larger, quasi-linear system). The cell bow echo, describing the bowing of an isolated cell, was not included due to the imposed spatial restrictions. The number of cases in each category are listed in Table 1.

3. CASE DESCRIPTIONS

Cases will now be presented from each of the mature structure classifications (classic bow echo, bow echo complex, and squall line bow echo). These cases were chosen as the most representative of their respective categories. Cases from each initiation type will not be presented at this time, due to their smaller dataset (as not all systems initiated within Oklahoma), and the lack of clearly discernible differences in surface patterns between systems of different initiation type yet similar mature structures.

Table 1: Number of Oklahoma bow echoes in each classification for 2002-2005. Columns are the mature structure, and rows are initiation type. See text for acronym explanation.

	CBE	BEC	SLBE	Total
Isolated	2	1	0	3
Merger	6	15	0	21
Linear	3	2	4	9
Unknown	4	4	1	9
Total	15	22	5	42

3.1 *13 March 2003: Classic Bow Echo (linear initiation type)*

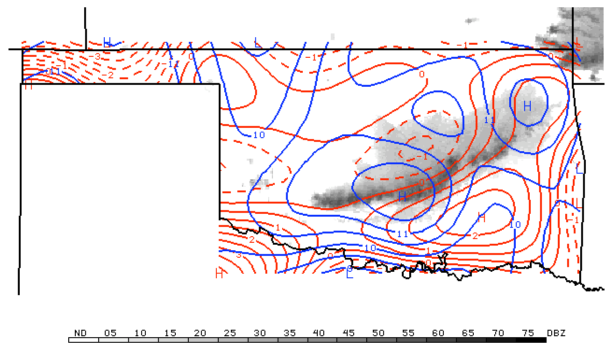
Convection first initiated with this case at 0215 UTC in north-central Oklahoma; a convective line stretching west-southwest to east-northeast approximately 225 km in length was in place by 0300 UTC (not shown). At 0430 UTC, a surface pressure pattern very similar to those commonly identified with squall line MCSs had developed: a mesohigh pressure region centered just behind this convective line, and a region of lower pressure (the wake low) situated behind that. A cold pool was approximately co-located with the mesohigh, and a slight rise in temperatures associated with the wake low. At this point, a very small region of stratiform precipitation had just begun to form. The mesohigh the shifted farther toward the southern (right) end of the line (nearer the growing stratiform region) as well as forward at 0530 UTC, so that it was almost centered on the line itself (not shown). The convective line began to bow slightly, and up until this time the cold pool remained spatially linked with the mesohigh.

A feature of interest appeared at 0545 UTC: the mesohigh surged noticeably ahead of the line while remaining slightly to the right of the bow apex (Fig. 1a). The cold pool, meanwhile, remained in its original place behind the line, centered behind the bow apex. One-half hour later at 0615 UTC, the bowing in the line expanded (Fig. 1b); however, the cold pool isotherms stayed approximately parallel to the bowed shape of the line, hinting at least initially that gravity-current dynamics might play a role in the bowing. However, the surging mesohigh away from the cold pool suggests other processes such as gravity wave dynamics and/or vertical transport of momentum were at play. More stratiform precipitation formed and filled in behind the line as it bowed further. As this stratiform region continued to develop, the convective line weakened; by 0830 UTC, the convection at what would have been the apex of the bow had nearly dissipated (Fig. 1c). During this same transition from convective to stratiform, the mesohigh drifted back until it was centered behind the convective line and firmly within the stratiform region. It once again became co-located with the cold pool.

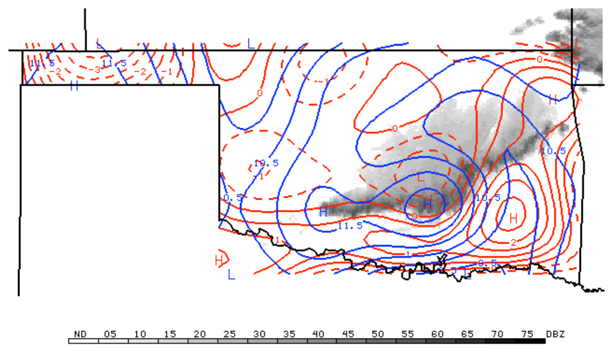
3.2 *17 May 2002: Bow Echo Complex (isolated initiation type)*

In this case, a mix of weakly organized convection and stratiform precipitation was already ongoing in the surrounding area when one isolated cell on the west-central Texas-Oklahoma border organized into a bowing system by 0415 UTC (not shown). At this time, the bow itself was only approximately 50 km in length. A mesohigh associated with the broader convection was visible, yet none could be seen that was associated specifically with this bow. It is possible that any mesohigh (and associated surge) generated solely by this newly formed bow would not be seen because of this other, stronger signal. The same can be said of the surface cold pool; only one tightly aligned with the larger mesohigh was visible. Over the next two hours, the bow continued to grow to a length of approximately 150 km, and a mesohigh directly associated with this bow (positioned just behind the convective line) became visible. By the end of this period, the mesohigh had shifted toward the western (right) end of the convective line. A cold pool specific to this bow also became clear, at first still co-located with the mesohigh.

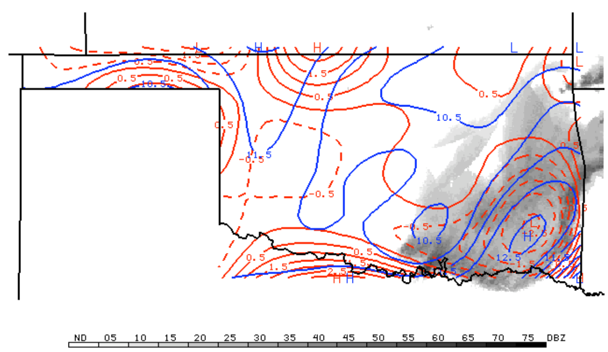
At 0615 UTC, the mesohigh surged ahead of the convective line, shown in Fig. 2a. As in the previous case, the isotherms delineating the cold pool remained more parallel to the line itself, with the cold pool centered behind the apex. Again, this pressure surge preceded strong bowing development, which began at 0645 UTC and continued until 0715 UTC (not shown). During this time, two severe wind reports were received by the National Weather Service, and there were also two greater than 20 m s-1 wind gusts reported by the Mesonet. Another pressure surge ahead of the convective line occurred at 0815 UTC (Fig. 2(b)); again the isotherms re-



(a) 0545 UTC 13 March 2003



(b) 0615 UTC 13 March 2003



(c) 0830 UTC 13 March 2003

Figure 1: WSI NOWrad data, in gray; overlying contours are 82.4-h high-pass filtered surface pressure and temperature. Pressure (blue) has been corrected to average Mesonet station height and has the diurnal cycle removed. Contours are every 0.25 hPa. Isotherms (red) are every 0.5 °C, with the negative contours dashed. In (a), the mesohigh surge ahead of the convective line can be observed; note the cold pool remains behind both surge and convective line. In (b), both the strongly delineated bowing after the mesohigh surge and the parallel nature of the isotherms to the bow can be clearly seen. In (c), the mesohigh and cold pool are again co-located, and positioned within the stratiform region of the convective system.

mained parallel, with the cold pool behind the bow. A period of increased bowing development followed (although not as intense as the first), from 0830 to 0900 UTC.

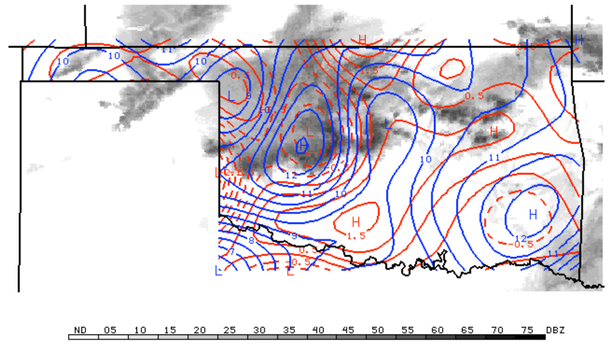
By 0915 UTC the mesohigh had shifted well back into the stratiform precipitation region, and was located near the area of most intense stratiform rain (see Fig. 2(c)). On the other hand, the cold pool remained closer to the convective line itself, still in its position centered behind the apex. After this point the bow echo began to dissipate. By 1115 UTC no radar reflectivities exceeding 55 dBZ associated with the system remained within the state (not shown).

3.3 *05 to 06 June 2003: Squall Line Bow Echo (linear convection type)*

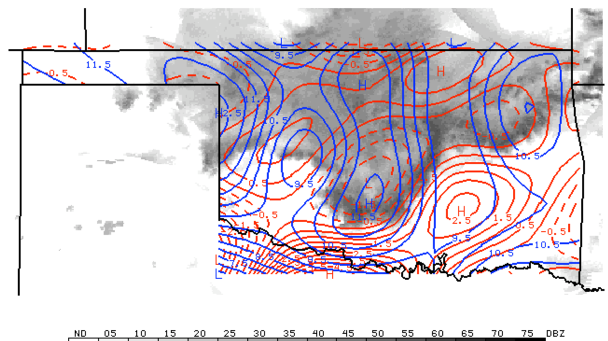
This case also began with weakly organized convection and stratiform precipitation in northwest Oklahoma, which formed into a squall line stretching southwest-northeast across the western half of the state by 0145 UTC 6 June (not shown). Some spotty areas of stratiform precipitation could be found at the northern (left) end of the line at that time. There was a mesohigh located directly with a cold pool, centered about 75 km behind the entirety of the squall line. At 0200 UTC, the mesohigh surged closer to the convective line, shown in Fig. 3(a). Like the other cases, the cold pool retained the same separation from the squall line. At this point, one could see a slight bow in the convective line, with the apex of this curve positioned to the left of the high pressure surge.

Immediately after this surge, a portion of the squall line bowed out farther, until the squall line bow echo was highly pronounced by 0230 UTC (Fig. 3(b)). At 0215 UTC, a portion of the cold pool actually surged slightly ahead on left side of the bowing portion of the convective line (not shown). By 0230 UTC, however, the cold pool was back behind the bow, with its isotherms parallel to the bow curvature. Between 0215 and 0230 UTC, the cold pool continued to be centered more behind the entire squall line system, not just the bowed-out portion like the mesohigh. Like the other cases, the cold pool was farther behind the line than the mesohigh at this point.

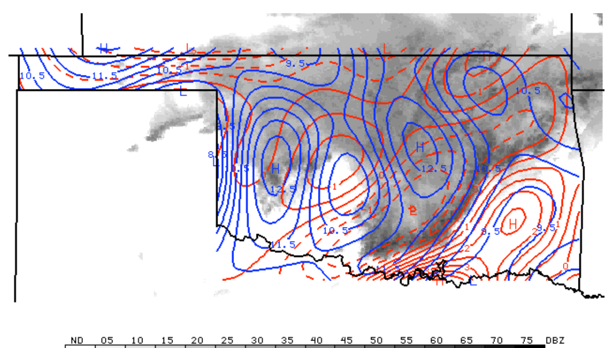
At 0230 UTC the isobars were also aligned similarly to the bow curvature, but by 0300 UTC (not shown) the mesohigh shifted so that it was again centered behind the entire squall line system. Minimal new stratiform precipitation was generated in that location, at least for the next two hours. During



(a) 0615 UTC 17 May 2002



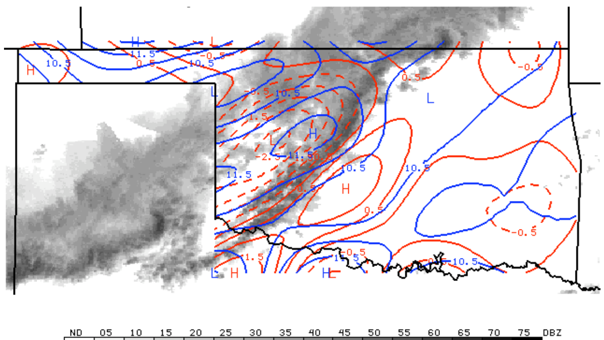
(b) 0815 UTC 17 May 2002



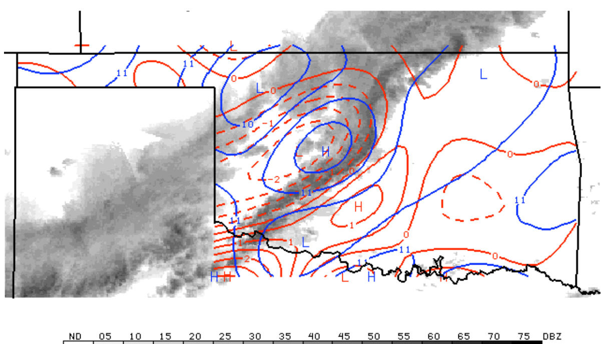
(c) 0915 UTC 17 May 2002

Figure 2: Plots are constructed as in Fig. 1. In (a) and (b) the mesohigh surges ahead of the convective line while the cold pool remains centered behind it. In (c) the mesohigh has shifted back until it is centered within the more intense stratiform precipitation. The cold pool, however, has remained closer to the convective line, in contrast to the previous case.

those hours, the convective line began to dissipate, and had converted to entirely stratiform precipitation by 0430 UTC (not shown). The mesohigh and cold pool remained centered behind the convective system, with the cold pool farther behind the line (approximately 50 km) than the mesohigh.



(a) 0200 UTC 06 June 2003



(b) 0230 UTC 06 June 2003

Figure 3: Plots are constructed as in Fig. 1(a). Note a forward surging of the isobars ahead of the convective line associated with the mesohigh in (a), while the cold pool remains behind the line. In (b), a new bowing segment has developed; the cold pool remains farther behind the line than the mesohigh.

4. DISCUSSION

After reviewing the surface data for all 42 cases, a surface pattern of ‘pressure surge - new bowing’ began to emerge which generally characterized bowing development. This pattern can be particularly seen in the above cases. Due to the spatial constraints of the dataset, surface features associated with new bowing could only be seen when the spatial extent of the bowing exceeded 50 km (the average distance between Mesonet stations). New bowing development which occurs directly from an isolated cell was too small to include (although many of the ‘isolated’ initiation style cases would exhibit this pattern later in their lifecycle, when they were larger than 50 km). Thus, the description below will assume the feature is either linear convection or an already bowing system, both longer than 50 km. This pattern includes the following stages, which are illustrated in Fig. 4.:

1. Quasi-linear convection forms, through any of the various initiation styles given herein. Both a mesohigh and a cold pool will be associated with this line, although the timing of the formation of these features is variable depending on presence of other convection and stratiform precipitation nearby. Typically, the mesohigh is located close to and just behind the convective line.

2. The mesohigh surges ahead of the convective line. The line might bow slightly at the same time, although bowing has not necessarily yet occurred.

3. The system enters a period of more intense bowing development. The apex of this new surge in radar reflectivity is located to the left (typically north) of the surge in pressure. The cold pool remains behind the convective line, its isotherms aligned with the line itself.

4. As more stratiform precipitation forms, the mesohigh and cold pool drift back until they are again co-located, now between the convective line and the region of stratiform precipitation. Note also that unlike a squall line, a pronounced shift in the stratiform region to the left end of the bow (an asymmetric structure) is not necessarily seen. The convective line dissipates.

Of the 42 cases examined, nine of them had all new bowing development either occurring outside of the Mesonet or being too small to be adequately sampled, leaving 33 cases. Of these, a pressure surge as depicted above occurred before new bowing development in 14 (42%) of the cases; with a mean time interval of 27 min. Pressure surges and new bowing were simultaneous, as best as can be determined from the available data, in ten cases. New bowing development actually preceded the pressure surge in five cases, with a mean time interval between the two of 38 min. However, of these five “before” cases, in three of them bowing occurred soon (within an hour) after the convective line entered the state; it is possible that a pressure surge did exist prior to the

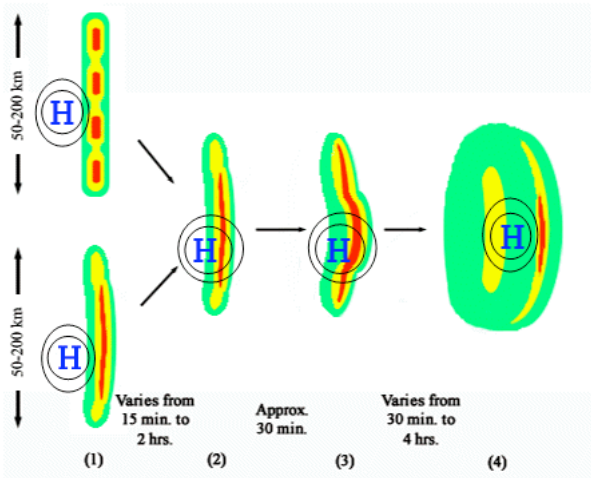


Figure 4: Schematic depicting the 'pressure surge - new bowing' pattern. Black contours are surface pressure. Green, yellow, and red shapes are increasing levels of radar reflectivity. Numbers 1 through 4 correspond to steps 1 through 4 as described in the text.

bowing but was not adequately captured in the objective analysis at the edge of the sampled region. In only four cases was there no surge whatsoever associated with new bowing development.

The existence of pressure surges associated with bowing in 88% of the cases is significant. While the greatest proportion of the cases exhibited surges preceding the bowing, this behavior was not observed in all cases. This differing timing of bowing and pressure surges may complicate interpretation of the dynamics of the bowing process; however, work is underway to unravel the salient mechanisms.

It should be noted that while the isobaric pattern illustrated in Fig. 4 fit well with a large percentage of cases, a similar conclusion could not be drawn for surface temperature. While the cold pool would generally follow the process described above, its positioning was much more variable, particularly with respect to its placement to the right or left of the bow apex. Thus, isotherms were not included in the schematic.

5. CONCLUSIONS

The Oklahoma Mesonet was used to create high-pass, temporally filtered surface data contours overlaid on WSI NOWrad composite radar data during years 2002 through 2005. Within these years, the radar data were examined for all bow echoes which were both large and long-lasting enough to be adequately sampled by the observation network. The resultant bow echoes were then subdivided into categories based on both structure when mature, and type of initiation.

The horizontal structure and temporal behavior of the surface pressure and temperature patterns associated with development of new bows or bowing segments within already organized convection is presented. Forty-two percent of the cases examined exhibited a pressure surge prior to new bowing growth. A conceptual model of this processes is proposed. This pattern was found within all classifications, of both structure and initiation category. Additionally, new bowing development was associated with a surge at some point (either before, prior, at the same time) in fully 88% of the cases. Most notable, however, is the lack of any similar feature associated with squall lines, perhaps pointing to a dynamical difference between the two modes of convection.

Current research is focused on possible causes of the surface pressure surges in relation to the bowing. A collaborative work with Pat Haertel is examining the possibility of gravity wave origin.

6. ACKNOWLEDGEMENTS

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